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DUAL-PLANET FREE-RETURN TRAJECTORIES TO VENUS AND MARS IN 1976 AND 1978

By Benjamin J. Garland

Advanced Mission Design Branch

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DUAL-PLANET FREE-RETURN TRAJECTORIES TO VENUS AND MARS IN 1976 AND 1978

By Benjamine J. Garland

SUMMARY

A study was made of free-return trajectories in 1976 and 1978 which pass near both Venus and Mars. The trajectories in 1976 were of only superficial interest because of the high injection velocity required. However, the results indicate that a spacecraft which is capable of achieving free-return trajectories to Mars in 1977 and 1979 will also be capable of achieving free-return trajectories to both Venus and Mars in 1978. In addition to passing close to Venus, these trajectories do not require the spacecraft to enter the asteroid belt.

INTRODUCTION

One of the major disadvantages of free-return trajectories to either Venus or Mars is that the spacecraft is near the target planet for only a small percentage of the total trip time. It was shown in reference 1 that a typical free-return trajectory to Mars requires between 650 and 710 days and that the spacecraft is within the sphere of influence of Mars for approximately 40 hours. Similarly, it was shown in reference 2 that a typical free-return trajectory to Venus requires between 330 and 390 days and that the spacecraft is within the sphere of influence of Venus for approximately 60 hours. Since any interplanetary mission will require a large effort, it is desirable to obtain as much useful information as is possible during any one mission.

In reference 3, Battin has described free-return trajectories in 1966 and 1972 which pass near both Venus and Mars before the spacecraft returns to Earth. The relative motions of Venus, Earth, and Mars are such that this type of trajectory is possible approximately every 6.5 years. Battin described these trajectories as astronomical oddities and stated that the launch-time tolerances appeared to be far too severe for current technology.

One objective of this study was to define the launch-time tolerances of dual-planet free-return trajectories to Venus and Mars in 1976 and 1978.

SYMBOLS

r	distance between body and the center of the Sun, A.U.
v	velocity, fps
λ	longitude of body in heliocentric ecliptic coordinate system, deg
λ_p	longitude of body in planet-centered coordinate system, deg
ξ	right ascension of hyperbolic excess vector, deg
ρ	distance of body from the center of the planet, A.U.
ϕ	latitude of body in heliocentric ecliptic coordinate system, deg
ϕ_p	latitude of body in planet-centered coordinate system, deg
ψ	declination of hyperbolic excess vector, deg

ANALYSIS

The two coordinate systems used are shown in figure 1 and have been discussed in references 1, 2, and 4. The ephemerides of the planets are described by noncoplanar ellipses whose elements vary with time. The orbital elements of planets were obtained from reference 5.

The dual-planet free-return trajectories are calculated using an extension of the method presented in references 1 and 4. The trajectories are treated as a series of single-planet free-return trajectories except that after encountering the first target planet the spacecraft travels to the second target planet instead of returning directly to Earth. The trajectory is specified by the departure date, the time of the first encounter, and the order in which the target planets are encountered.

The periapsis altitude at the first target planet may be controlled by changing the time of flight between Earth and the first target planet. It was shown in reference 2 that for a specified departure date, there might be a maximum periapsis altitude at the target planet. This condition is also true in dual-planet free-return flybys, but the situation is complicated further by the fact that the periapsis altitude at the second target planet must be above the surface of the planet.

The periapsis altitude at Venus and Mars are presented in figure 2 as a function of the flight time between Earth and Venus. This trajectory leaves Earth on December 7, 1978. The periapsis altitude at Venus is positive if the Earth-Venus trip time is between 145.6 and 164.5 days. Unfortunately, the periapsis altitude at Mars is negative if the Earth-Venus flight time is between 152.9 and 158.0 days. Therefore, dual-planet free-return trajectories beginning on this date are possible only if the Earth-Venus flight time is between 145.6 and 152.9 days and between 158.0 and 164.5 days. Trajectories occurring in the second interval are of the most interest since the periapsis altitudes at both Venus and Mars are relatively low.

The conversions between Julian Dates and the Gregorian Calendar during the time periods discussed are presented in the table.

RESULTS

The dual-planet free-return trajectories considered in this study encounter Venus first and then Mars. Two time periods were considered but more emphasis was placed on the second interval because a lower injection velocity was required during this interval. The first interval occurs in 1976 and the second occurs in 1978.

The injection velocity, entry velocity, and total trip time for dual-planet free-return trajectories beginning between 2 443 070 J.D. (October 18, 1976) and 2 443 085 J.D. (November 2, 1976) are presented in figure 3. The quantities presented are for the trajectory which requires the lowest injection velocity on a given departure date. The minimum injection velocity on a given departure date. The minimum injection velocity, 15 940 fps, occurs when the departure date is 2 443 078 J.D. It is impossible to achieve a dual-planet free-return trajectory before 2 443 071 J.D. and after 2 443 085 J.D. because the injection velocity increases rapidly. The 14-day departure window presented in figure 3 would require an increase of approximately 460 fps in the injection velocity. The entry velocity is between 54 400 fps and

57 400 fps, and the total trip time is between 715 and 736 days.

Characteristics of Trajectories Occurring Between November 23, 1978 and December 27, 1978

The dual-planet free-return trajectories beginning in 1978 are of more interest because lower injection velocities are required. Some of the characteristics of this group of trajectories are presented in figures 4(a) through 4(h) as functions of the departure date and the periapsis altitude at Venus. The departure dates vary between 2 443 836 J.D. (November 23, 1978) and 2 443 870 J.D. (December 27, 1978).

The periapsis altitude at Mars is shown in figure 4(a). The periapsis altitude at Venus and Mars are both zero when the departure date is 2 443 836 J.S. (November 23, 1978). The periapsis altitude at one of the target planets is determined by the departure date and the periapsis altitude at the other target planet.

The required injection velocity is presented in figure 4(b). The minimum injection velocity is approximately 14 220 fps. It occurs on 2 443 848 J.D. and gives a zero periapsis altitude at Mars. If the periapsis altitude at Venus is 200 n. mi., the minimum injection velocity is approximately 14 400 fps. An injection velocity of 15 380 fps is required to achieve a 30-day window if the periapsis altitude at Venus is 200 n. mi., an increase of 980 fps over the minimum velocity. The periapsis altitude at Mars varies from 145 n. mi. at the beginning of the window to 580 n. mi. at the end of the window. These results are comparable to the injection velocities for free-return trajectories to Mars in 1977 and 1979 (ref. 1). If the periapsis altitude at Mars is 200 n. mi., a 30-day window in 1977 requires an injection velocity of 15 360 fps and a 30-day window in 1979 requires an injection velocity of 15 180 fps.

The entry velocity at Earth is presented in figure 4(c). The entry velocity varies between 45 800 fps and 53 100 fps for all the trajectories considered. The entry velocity decreases as the periapsis altitude at Venus is increased. If the periapsis altitude at Venus is constant, the entry velocity will be increased as the departure from Earth is delayed. The entry velocity for the dual-planet free-return trajectory may be as much as 4 000 fps higher than the entry velocity for free-return trajectories to Mars in 1977 and 1979.

The time required to travel from Earth to Venus (Earth-Venus trip time) and the time required to travel from Venus to Mars (Venus-Mars flight time) are shown in figure 4(d). The Earth-Venus trip time varies from 182 to 141 days as the departure date is changed. The maximum change in the trip time on a given departure date was between 6 and 8 days.

The Venus-Mars trip time varies from 227 to 280 days. The trip time decreases as the periapsis altitude at Venus is increased. The time required to travel from Mars to Earth (Mars-Earth trip time) and the total trip time are presented in figure 4(e). The Mars-Earth trip time varies between 234 and 255 days. The maximum change for a fixed departure date is about 18 days. Unlike the Earth-Venus trip time and the Venus-Mars trip time, the Mars-Earth trip time increases as the periapsis altitude at Venus is increased.

The total trip time varies between 626 and 673 days. The total trip time depends more on the periapsis altitude at Venus than on the departure date. The total trip time can be changed as much as 37 days by changing the periapsis altitude at Venus, and it is decreased as this altitude is increased. The total trip time of the dual-planet free-return trajectory is slightly less than the time required for trajectories to Mars in 1977 and 1979.

The periapsis velocity at Venus and the angle between the periapsis position vector and the line connecting the centers of Venus and the Sun (spacecraft-Venus-Sun angle at periapsis) are presented in figure 4(f). The periapsis velocity varies between 45 600 fps and 52 800 fps. The minimum periapsis velocity for a 200-n. mi. altitude is 48 000 fps. The dual-planet free-return trajectories result in periapsis velocities at Venus which are approximately 10 000 fps higher than those encountered by free-return trajectories to Venus between 1970 and 1975. The spacecraft-Venus-Sun angle at periapsis is between 100° and 105°. This means that the periapsis is within 15° of the terminator and is on the dark side of Venus. The periapsis is within 15° of the subsolar point for free-return trajectories to Venus only.

The periapsis velocity at Mars and the angle between the periapsis position vector and the line connecting the centers of Mars and the Sun (spacecraft-Mars-Sun angle at periapsis) are presented in figure 4(g). The maximum value of the periapsis velocity is 26 200 fps and the minimum value is 23 600 fps. The maximum variation for any given departure date is approximately 1000 fps. The periapsis velocity is between 32 000 fps and 35 000 fps for free-return trajectories to Mars in 1977. In 1979 the periapsis velocity at Mars is between 36 500 fps and 38 500 fps. The spacecraft-Mars-Sun angle at periapsis is between 115° and 125°. That is, the periapsis is between 25° and 35° of the terminator and is on the dark side of Mars. The periapsis is about 15° from the terminator and on the dark side for free-return trajectories to Mars in 1977 and 1979.

The direction and magnitude of the hyperbolic excess at departure from Earth is presented in figure 4(h). The magnitude of the hyperbolic excess vector (hyperbolic excess) and the injection velocity are directly related so that this portion of the figure does not present much additional information. The declination of the hyperbolic excess is between 13° and 17° for the departure dates considered and is only slightly affected by the periapsis altitude at Venus. The right ascension of the hyperbolic excess vector is between 4° and -33°. The right ascension may vary as much as 15° on any departure date.

A Typical Dual-Planet Trajectory to Mars and Venus

The time history of a typical dual-planet free-return trajectory to Mars and Venus was calculated and the projection of this trajectory into the ecliptic plane is presented in figure 5. The spacecraft leaves Earth on December 7, 1977, and passes through perihelion before it reaches Venus on May 17, 1979. The spacecraft passes close to Mars on January 17, 1980, and returns to Earth on September 22, 1980. During this time the spacecraft has traveled through about 1.75 revolutions and has passed through one aphelion and two different perihelions. The periapsis altitude was 403.58 n. mi. and 302.22 n. mi. at Venus and Mars, respectively.

The time histories of the distance of the spacecraft from Earth and the distance of the spacecraft from the Sun are presented in figure 6 for the same trajectory. The spacecraft is 1.43 A.U. from Earth at the flyby of Venus and is 0.80 A.U. from Earth at the flyby of Mars. The closest approach to the Sun occurs at the first perihelion and is 0.53 A.U. At the second perihelion, the distance of the spacecraft from the Sun is 0.84 A.U. The maximum distance of the spacecraft from the Sun is 1.68 A.U., and occurs shortly before Mars is reached. One of the major disadvantages of the trajectories discussed in reference 1 is that the spacecraft must spend about one year in the asteroid belt, which can be assumed to begin at about 1.75 A.U. from the Sun (ref. 4). None of the dual-planet free-return trajectories studied require the spacecraft to enter the asteroid belt.

The motion of the spacecraft while it is close to the periapsis at Venus is presented in figure 7. The altitude is less than 1000 n. mi. for approximately 9 minutes. The spacecraft approaches Venus from the light side and its track on the surface of Venus crosses the terminator about 1.6 minutes before periapsis is reached. The spacecraft enters the umbra of Venus about 2.4 minutes after periapsis passage. The spacecraft is still in darkness 11.4 minutes after periapsis passage when the altitude has increased to one planet radii (3293.7 n. mi.).

Figure 8 presents the motion of the spacecraft near the periapsis at Mars. The spacecraft approaches Mars from the dark side and enters the umbra of Mars 14.8 minutes prior to the periapsis passage. The altitude is 2250 n. mi. (approximately 1.22 planet radii) when the spacecraft enters the umbra. The spacecraft emerges from the umbra approximately 0.2 minutes after periapsis passage and its track on the surface of Mars crosses the terminator 1.2 minutes later. The altitude of the spacecraft is less than 1000 n. mi. for 16 minutes but only slightly less than one-half of this time is in sunlight. The altitude has increased to one planet radius (1843.9 n. mi.) by 12.8 minutes after the periapsis passage.

CONCLUDING REMARKS

Dual-planet free-return trajectories to Venus and Mars occur in 1976 and 1978. The trajectories beginning in 1976 require injection velocities of at least 15 940 fps and the total trip times are between 715 and 736 days. The minimum injection velocity required by the group of trajectories beginning in 1978 is 14 220 fps and the total trip times are between 626 and 673 days. The lower injection velocities and shorter total trip times are important reasons why the 1978 trajectories are of the most interest.

It is not possible to specify the periapsis altitude at both Venus and Mars. However, it is possible to keep the periapsis altitude below 800 n. mi. at both planets by restricting the variation in the Earth-Venus trip time to less than approximately 6 days. For the cases considered, an increase in the periapsis altitude will cause a decrease in the periapsis altitude at Mars.

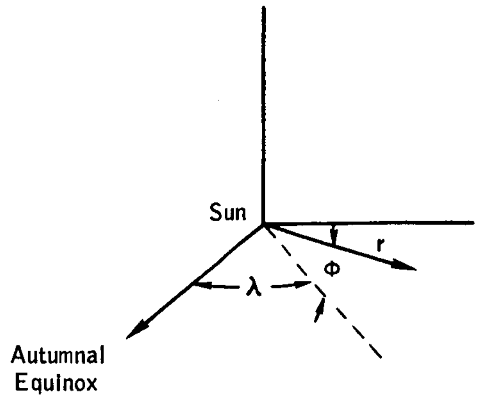
The periapsides at both Venus and Mars lie within 15° of the terminator and are on the dark side of the planet. The spacecraft approaches Venus from the light side, and it approaches Mars from the dark side. The spacecraft will spend some time in the shadow of both Venus and Mars.

The injection velocity required to achieve a 30-day launch window is approximately the same for dual-planet free-return trajectories in 1978 and for free-return trajectories to Mars in 1977 and 1979. The entry velocities of the dual-planet free-return trajectories in 1978 are about 4000 fps higher than the entry velocities of free-return trajectories to Mars in 1977 and 1979. The total trip times required for the dual-planet free-return trajectories in 1978 is slightly less than the total trip times required for free-return trajectories to Mars in 1977 and 1979. Although free-return trajectories to Mars in 1977 and 1979 require the spacecraft to spend approximately one year in the asteroid belt, the spacecraft will not enter the asteroid belt during a dual-planet free-return mission.

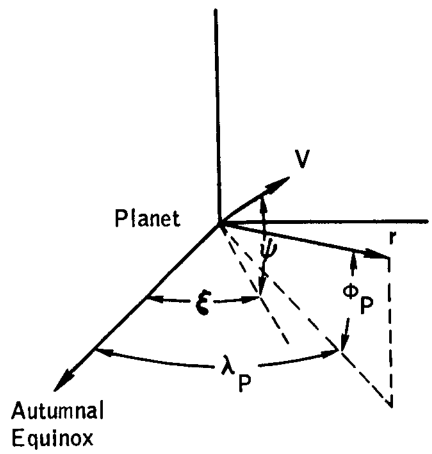
It appears that a spacecraft which is capable of achieving free-return trajectories to Mars in 1977 and 1979 will also be capable of performing dual-planet free-return trajectories to Venus and Mars in 1978.

CONVERSIONS BETWEEN JULIAN DATES AND
GREGORIAN CALENDAR DATES

Julian date	Gregorian calendar dates
2 443 070	October 18, 1976
2 443 075	October 23, 1976
2 443 080	October 28, 1976
2 443 085	November 2, 1976
2 443 830	November 17, 1978
2 443 840	November 27, 1978
2 443 850	December 7, 1978
2 443 860	December 17, 1978
2 443 870	December 27, 1978
2 443 880	January 6, 1979



(a) Heliocentric ecliptic system



(b) Planet centered system

Figure 1. - Heliocentric ecliptic and planet-centered coordinate systems.

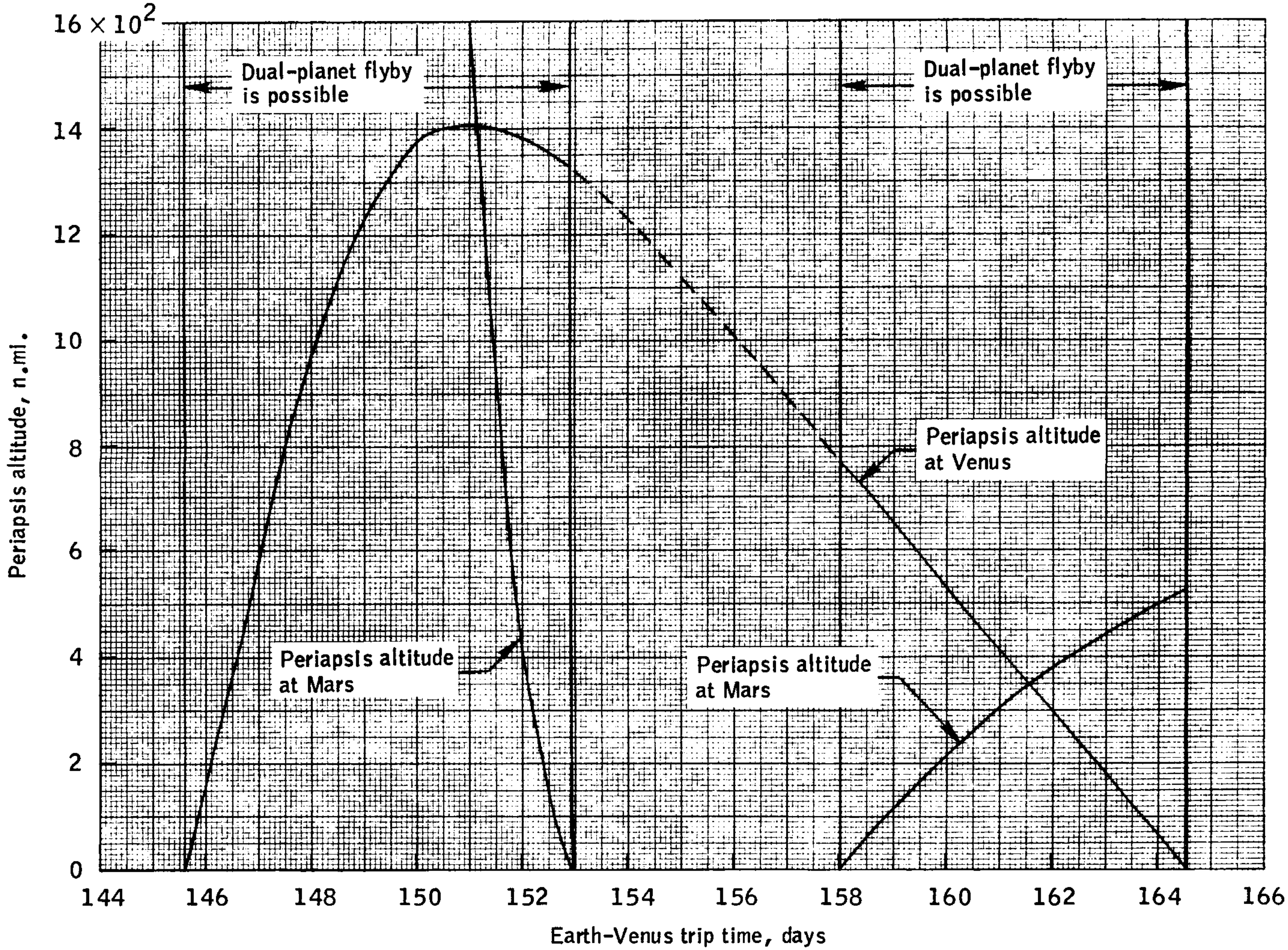


Figure 2.- Injection velocity, entry velocity, and total trip time for dual-planet flybys beginning between October 18, 1976 and November 2, 1976.

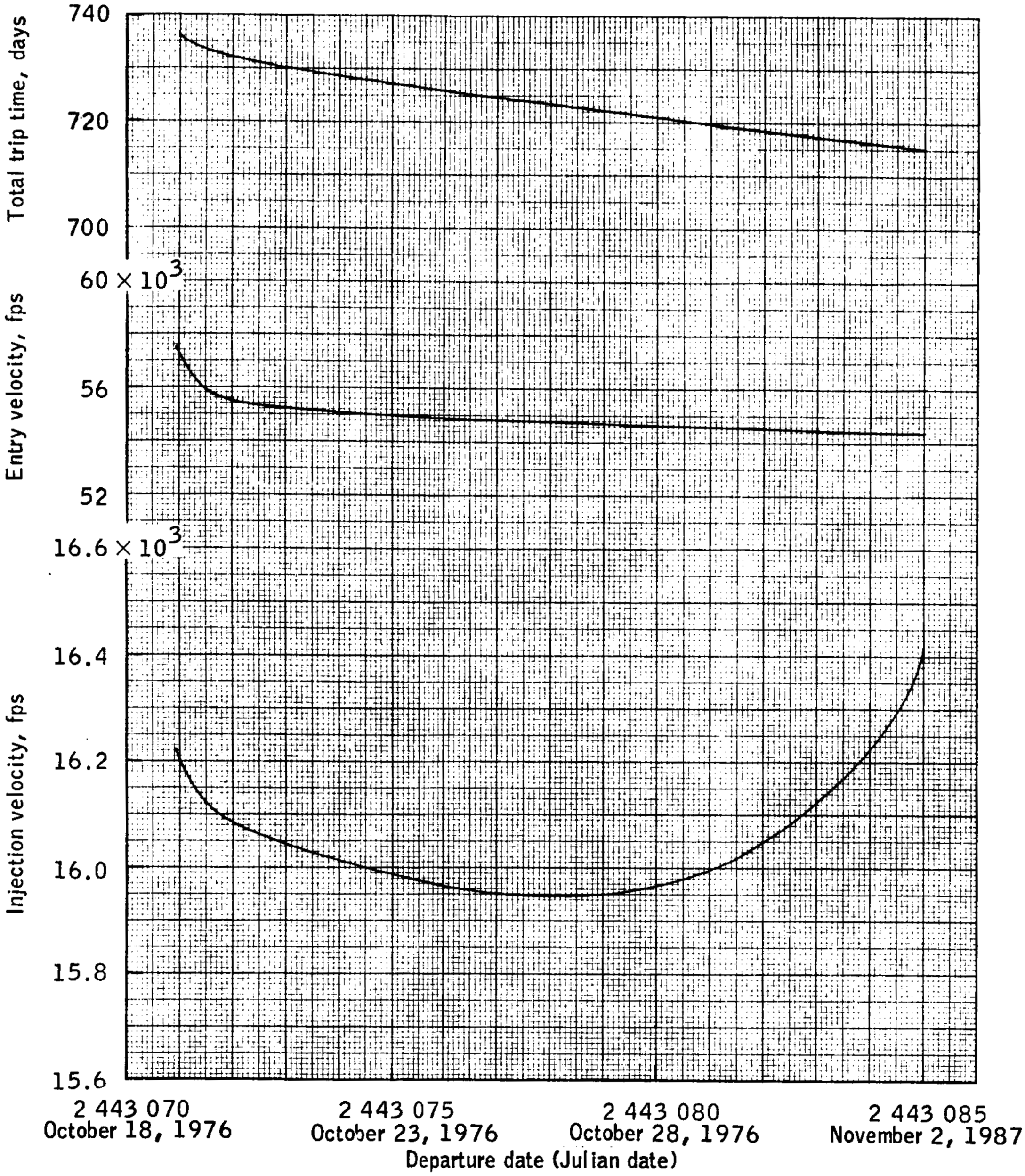
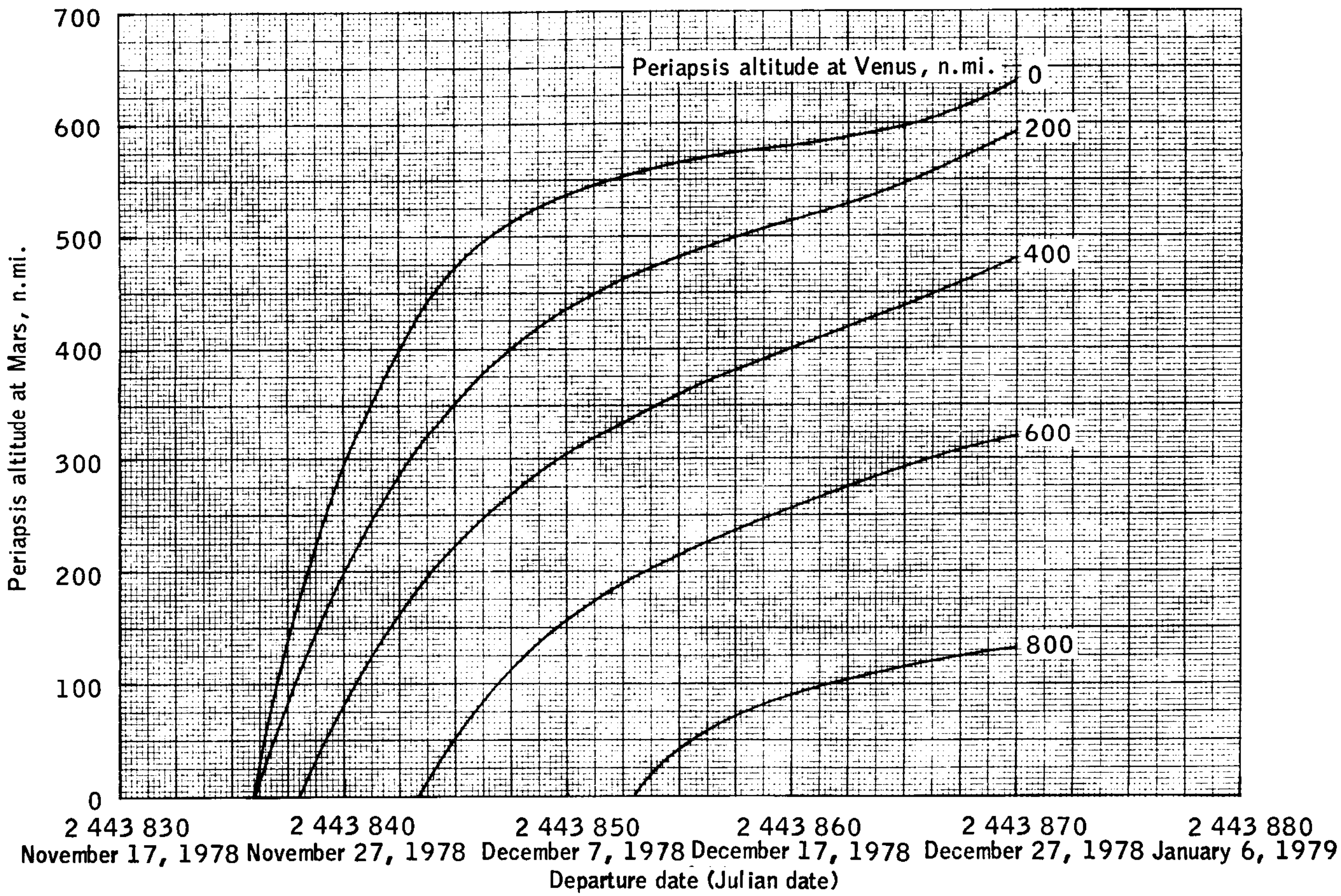
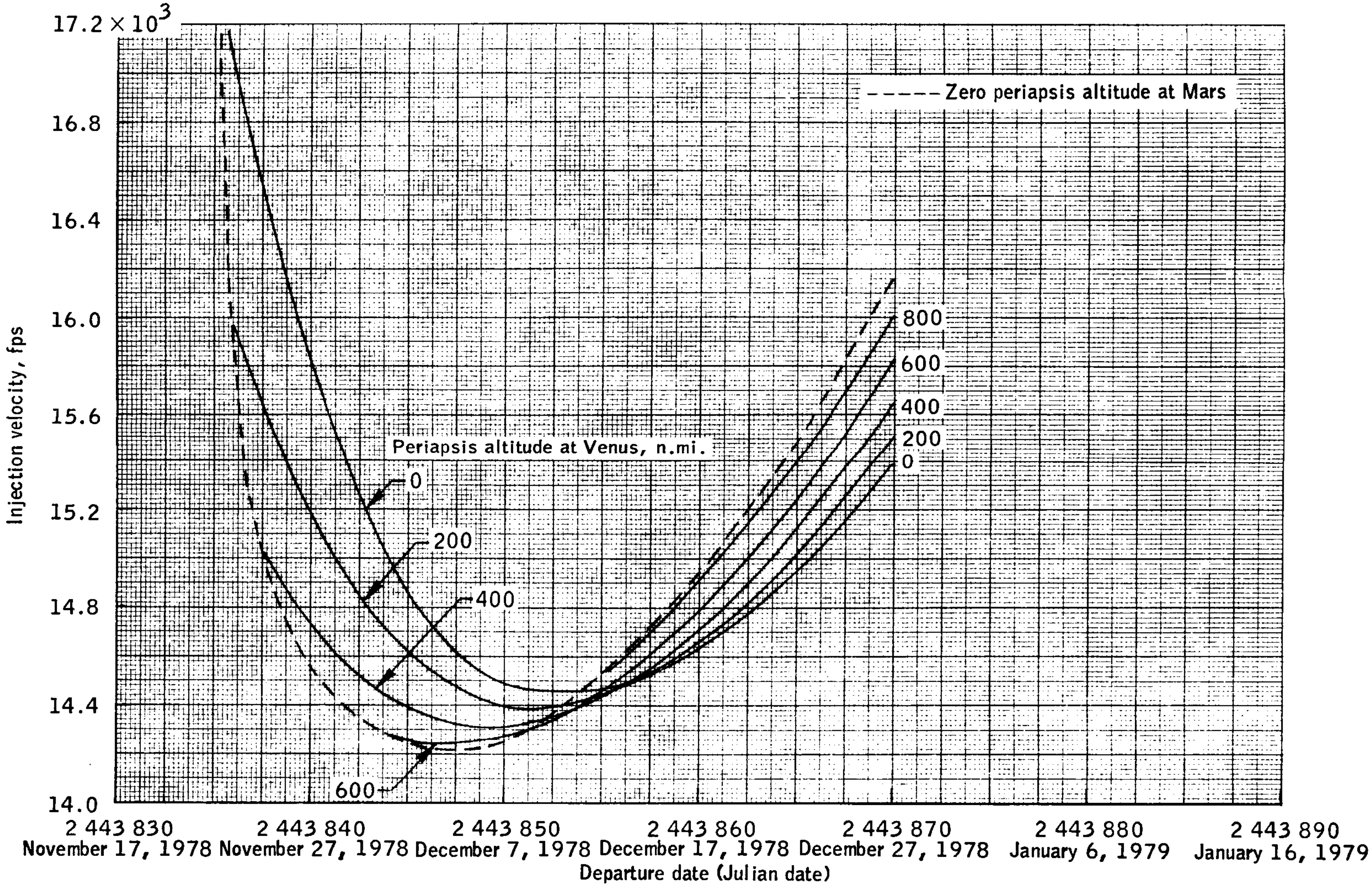


Figure 3.- Injection velocity, entry velocity, and total trip time for dual-planet flybys beginning between 2 443 070 Julian date (October 18, 1976) and 2 443 085 Julian date (November 2, 1976).



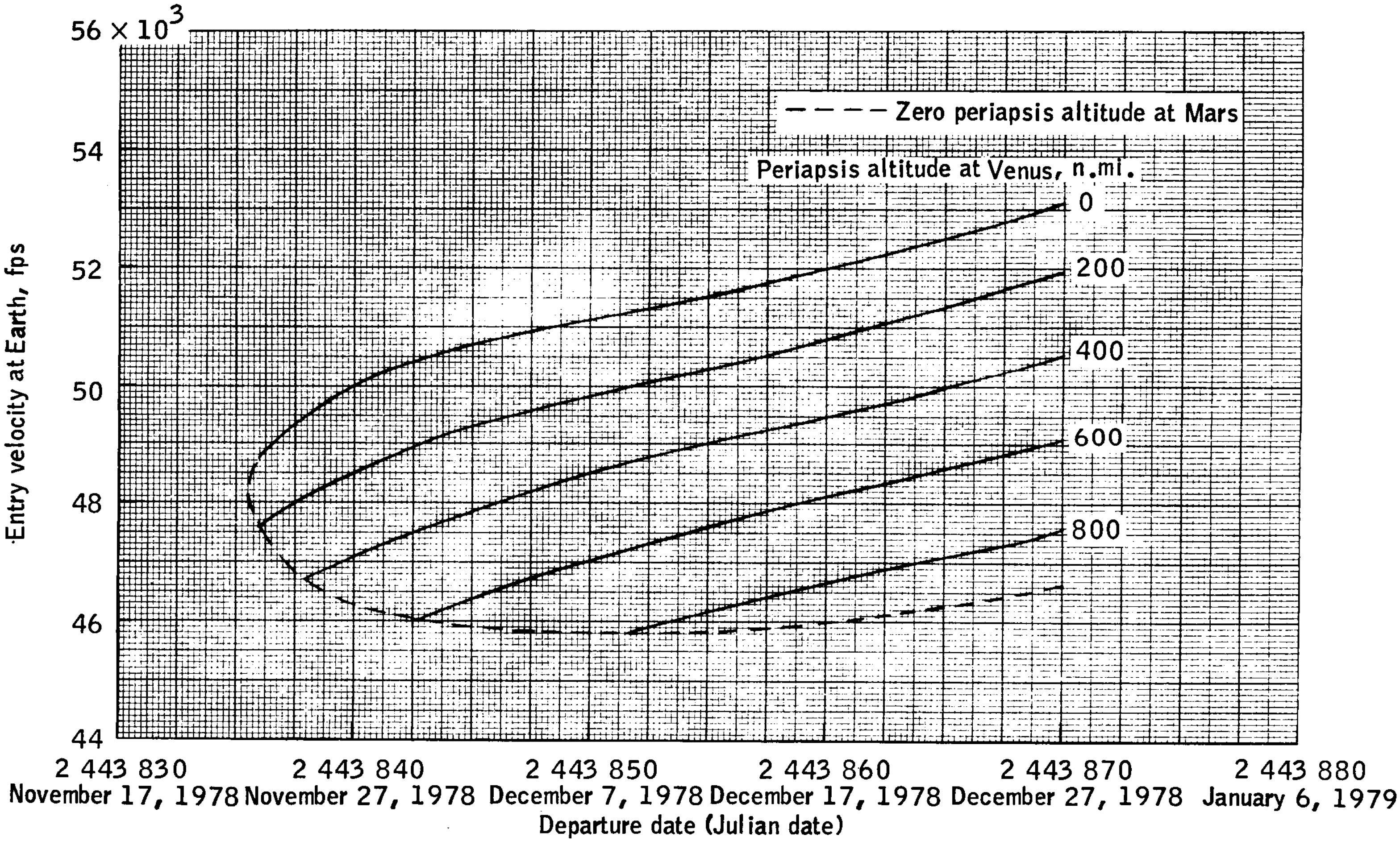
(a) Periapsis altitude at Mars.

Figure 4.- Characteristics of dual-planet flybys beginning between November 28, 1978 and December 27,1978.



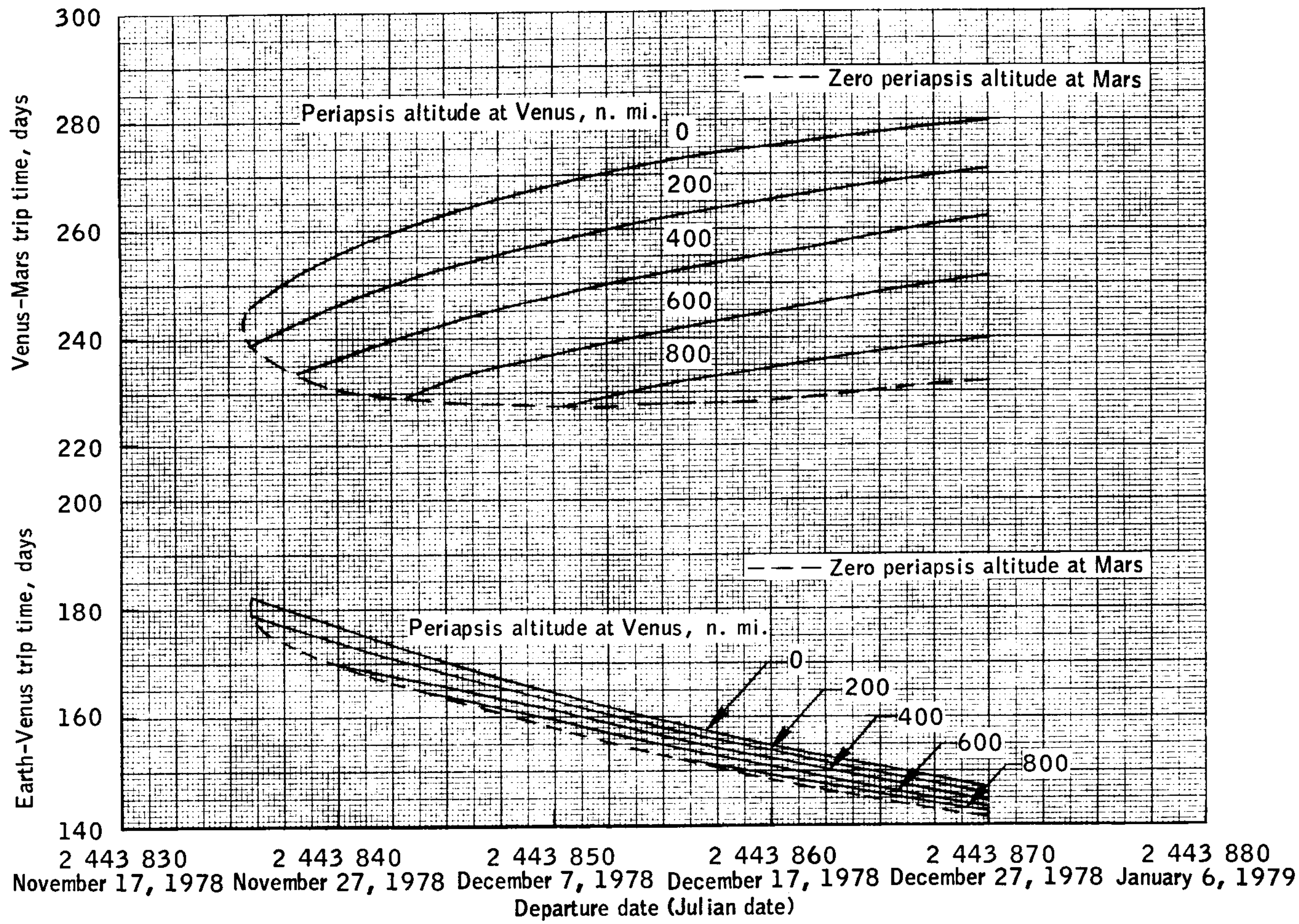
(b) Injection velocity.

Figure 4.- Continued.



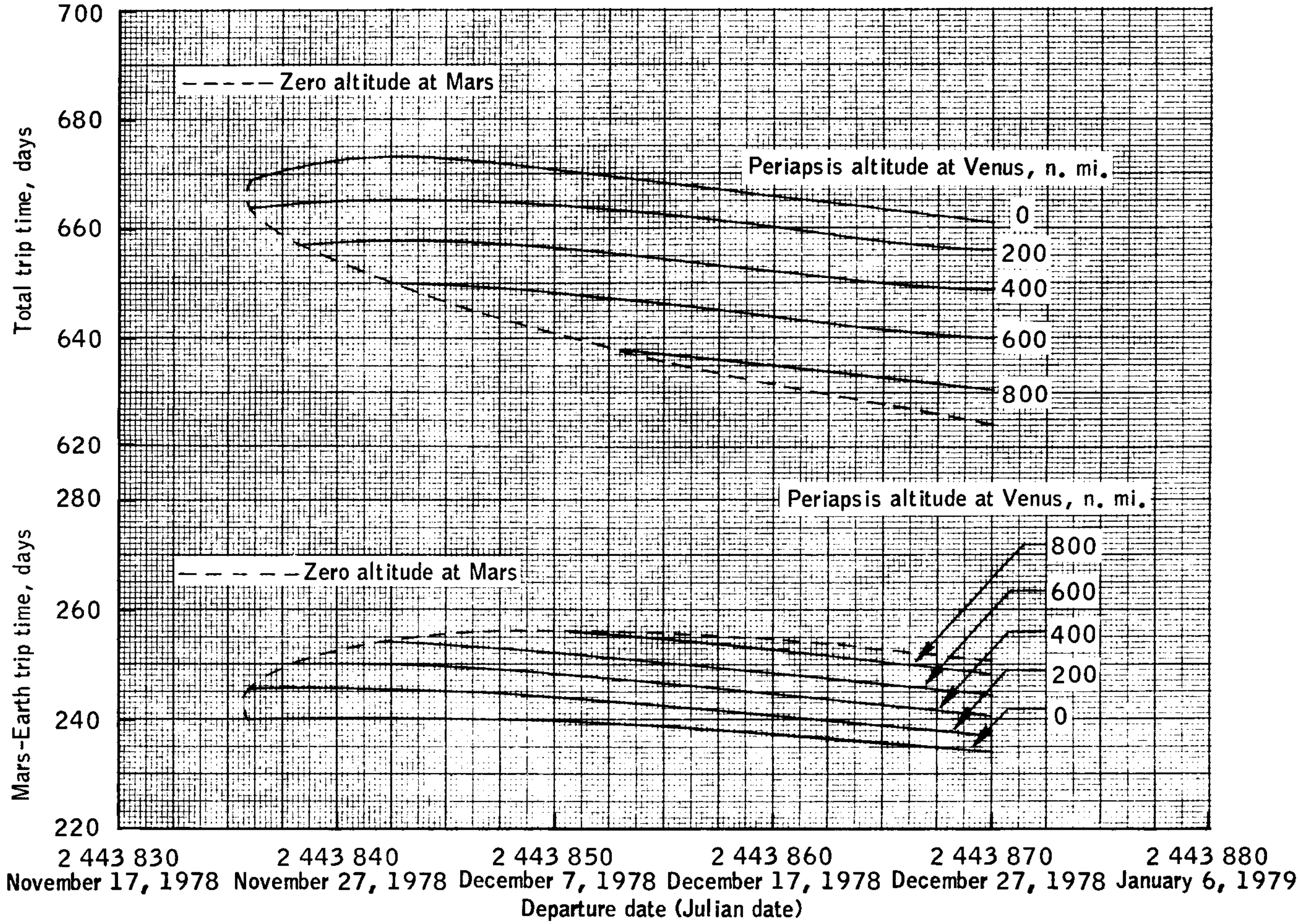
(c) Entry velocity at Earth.

Figure 4.- continued.



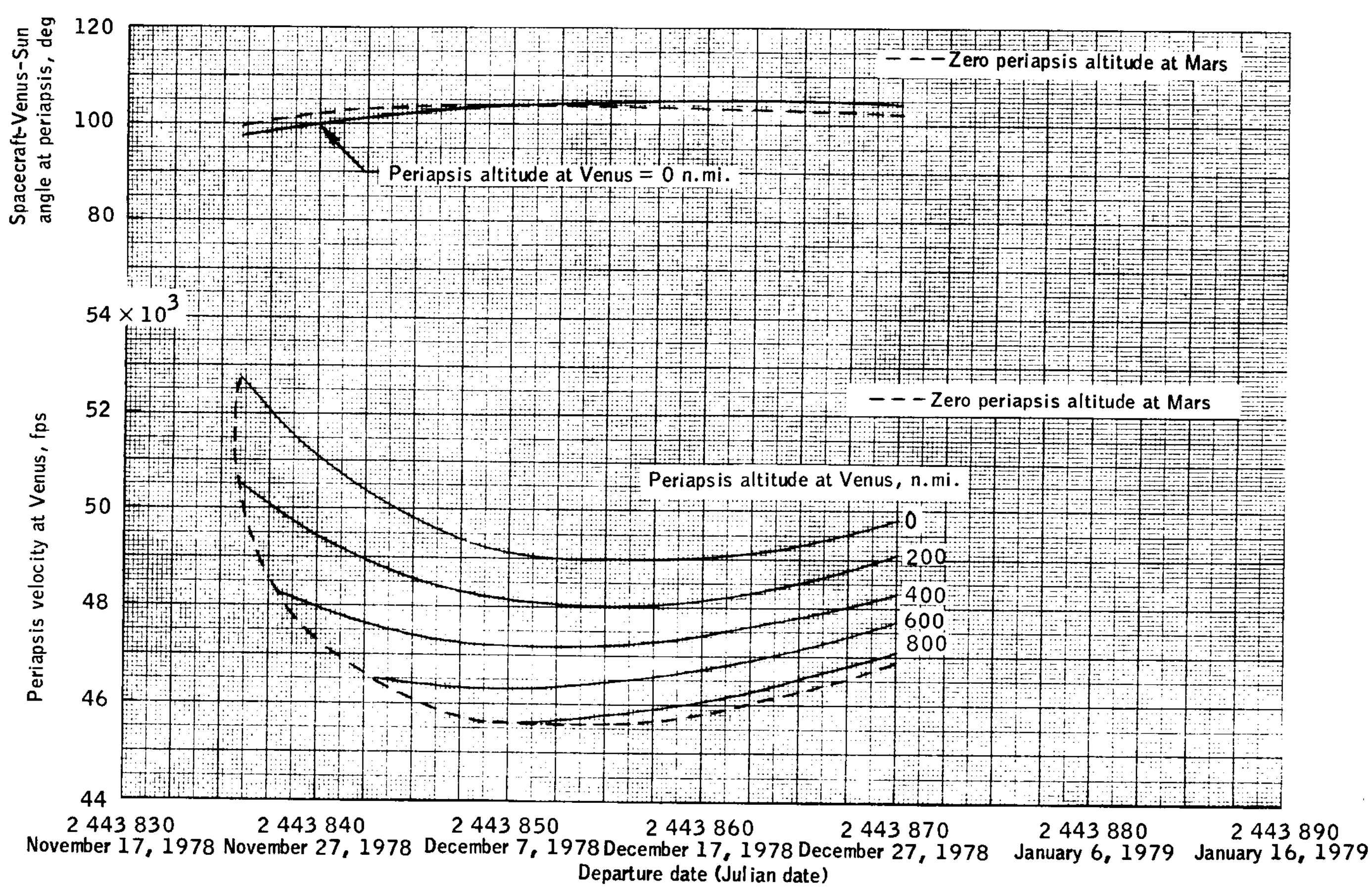
(d) Earth-Venus trip time and Venus-Mars trip time.

Figure 4.- Continued.



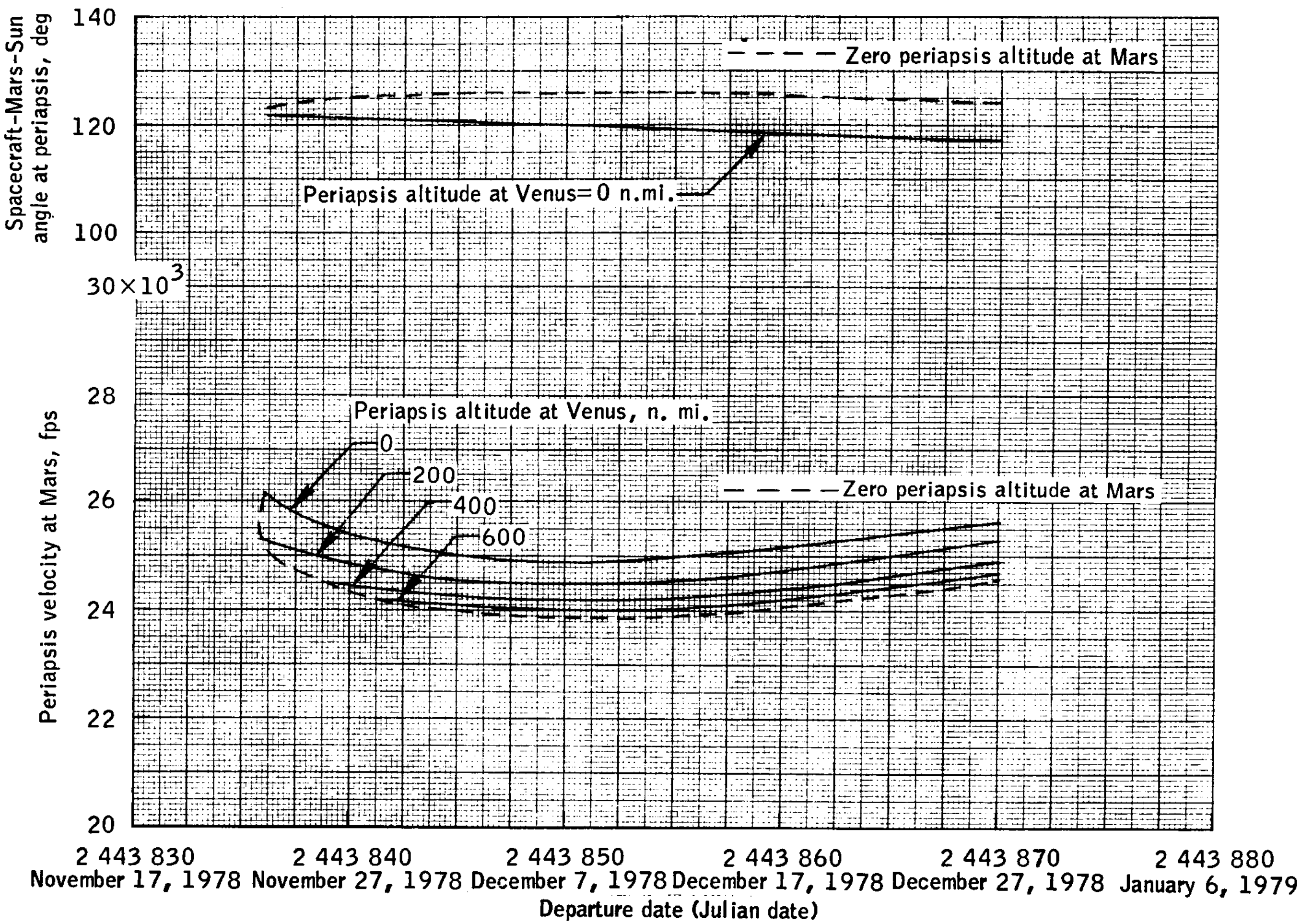
(e) Mars-Earth trip time and total trip time.

Figure 4.- Continued.



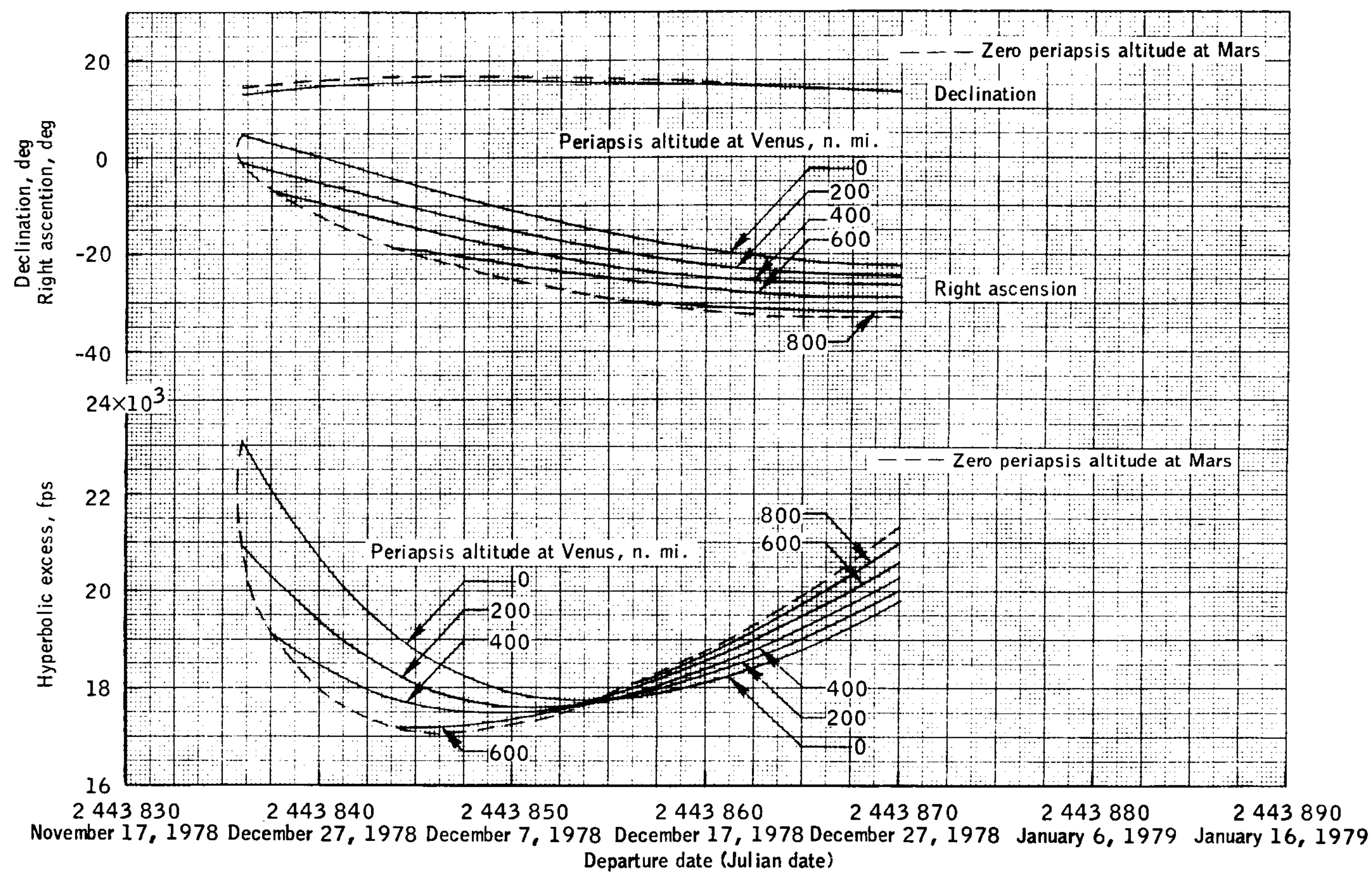
(f) Periapsis velocity at Venus and spacecraft-Venus-Sun angle at periapsis.

Figure 4.- Continued.



(g) Periapsis velocity at Mars and spacecraft-Mars-Sun angle at periapsis.

Figure 4.- Continued.



(h) Direction and magnitude of hyperbolic excess velocity vector at departure from Earth.

Figure 4.- Concluded.

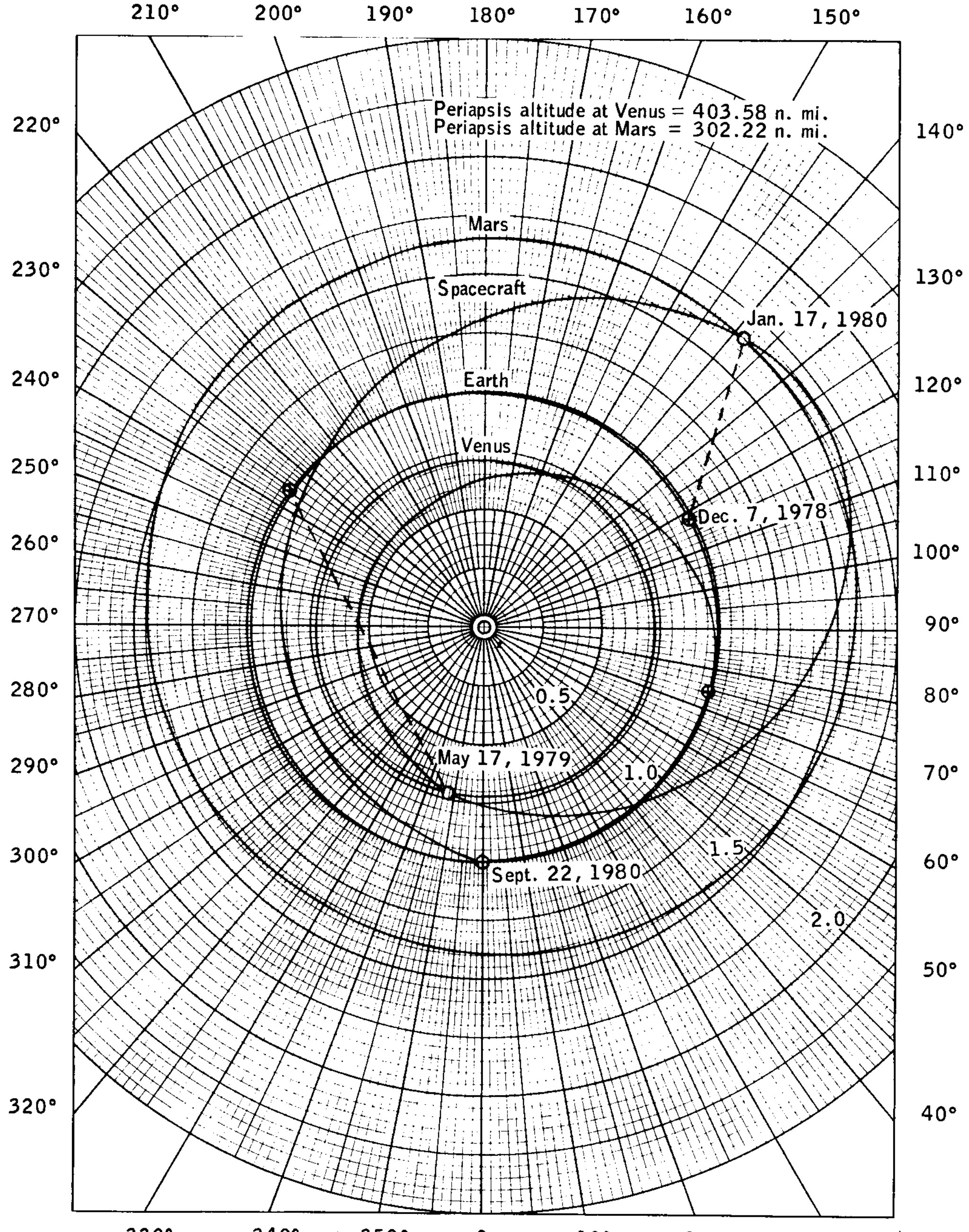


Figure 5.- Projection of dual-planet flyby trajectory beginning on December 7, 1978 into the ecliptic plane.

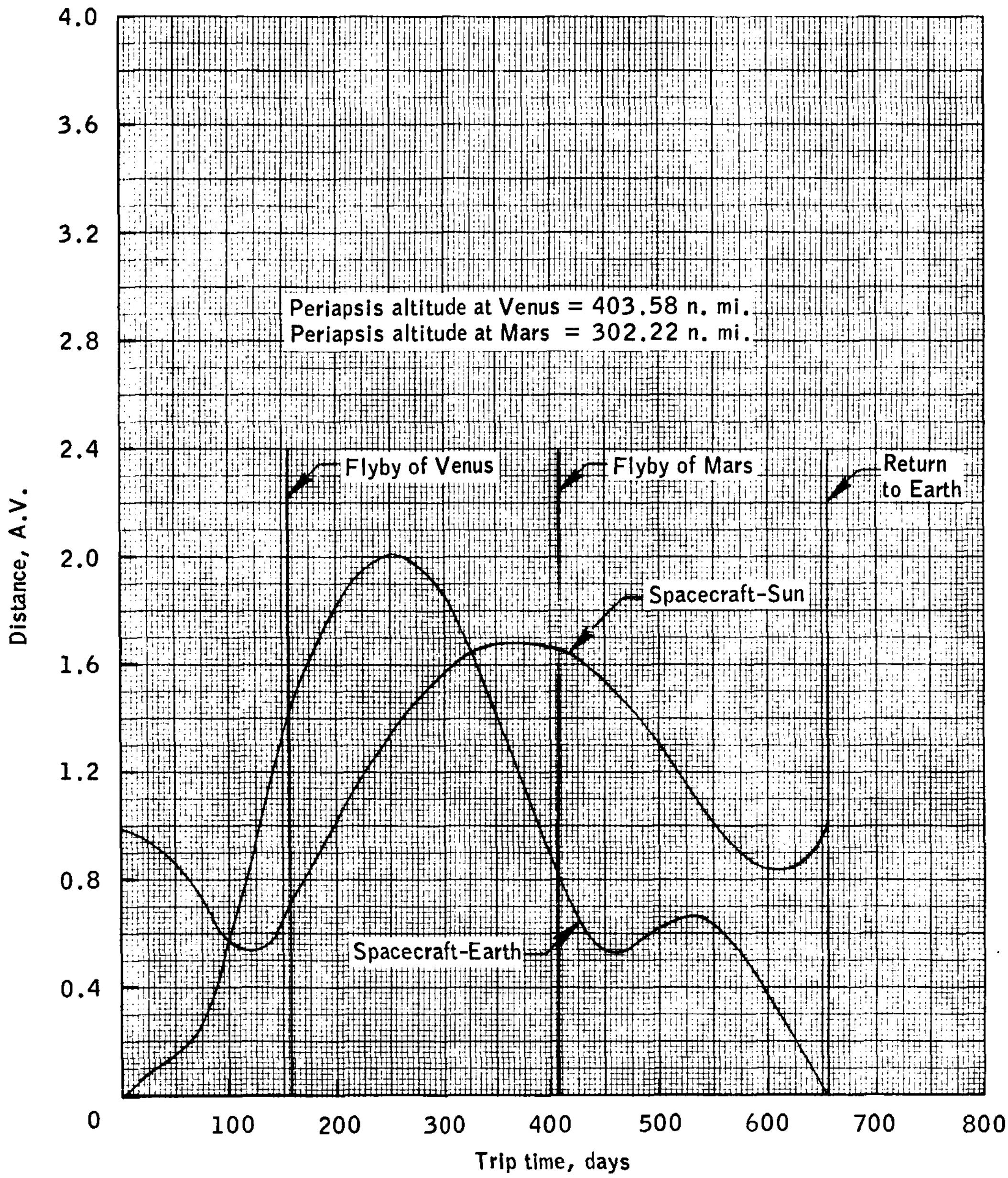


Figure 6.- Time history of distance of spacecraft from Earth and the Sun for trajectory beginning on December 7, 1978.

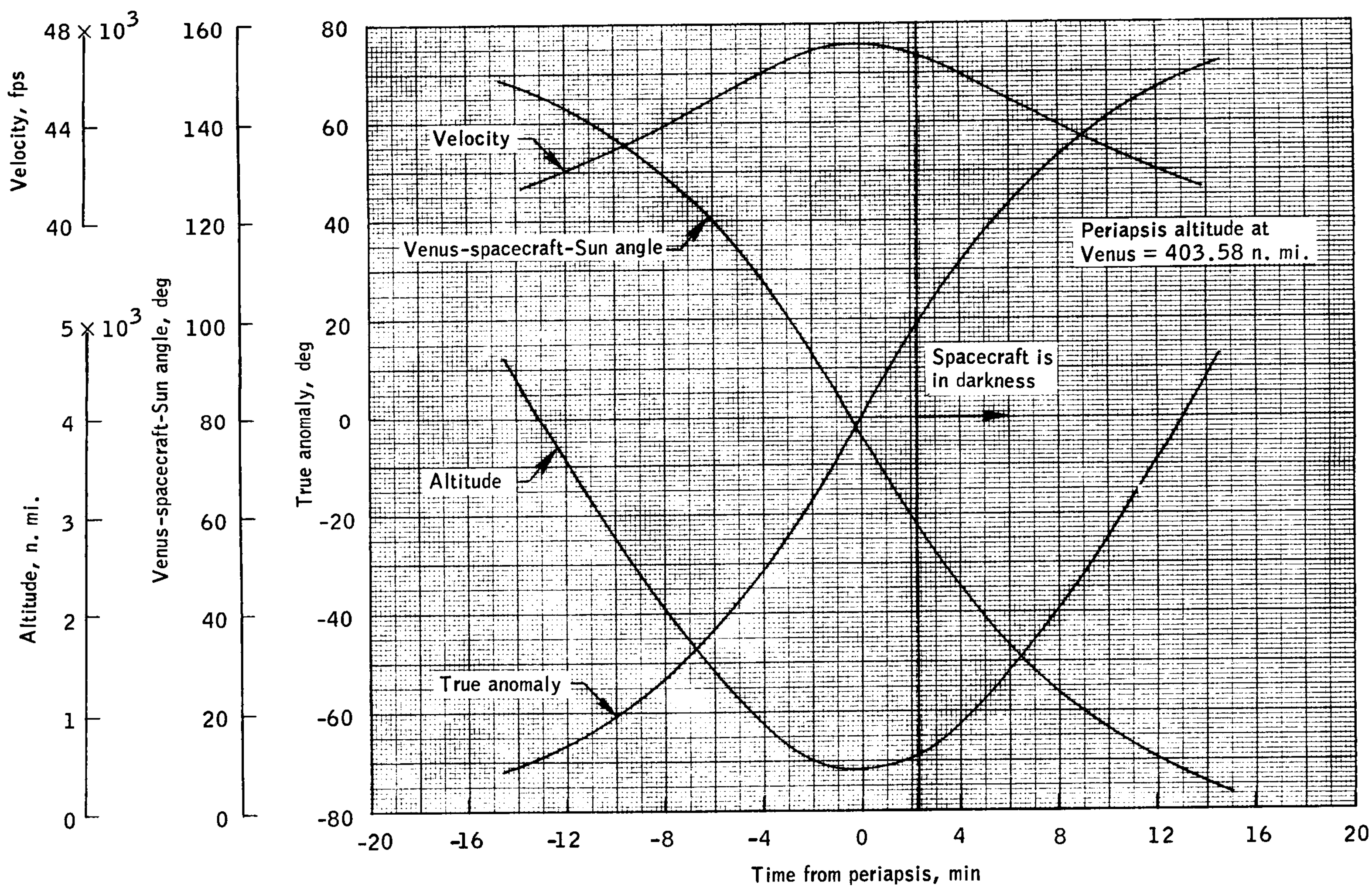


Figure 7.- Motion of spacecraft near Venus when the departure date is December 7, 1978.

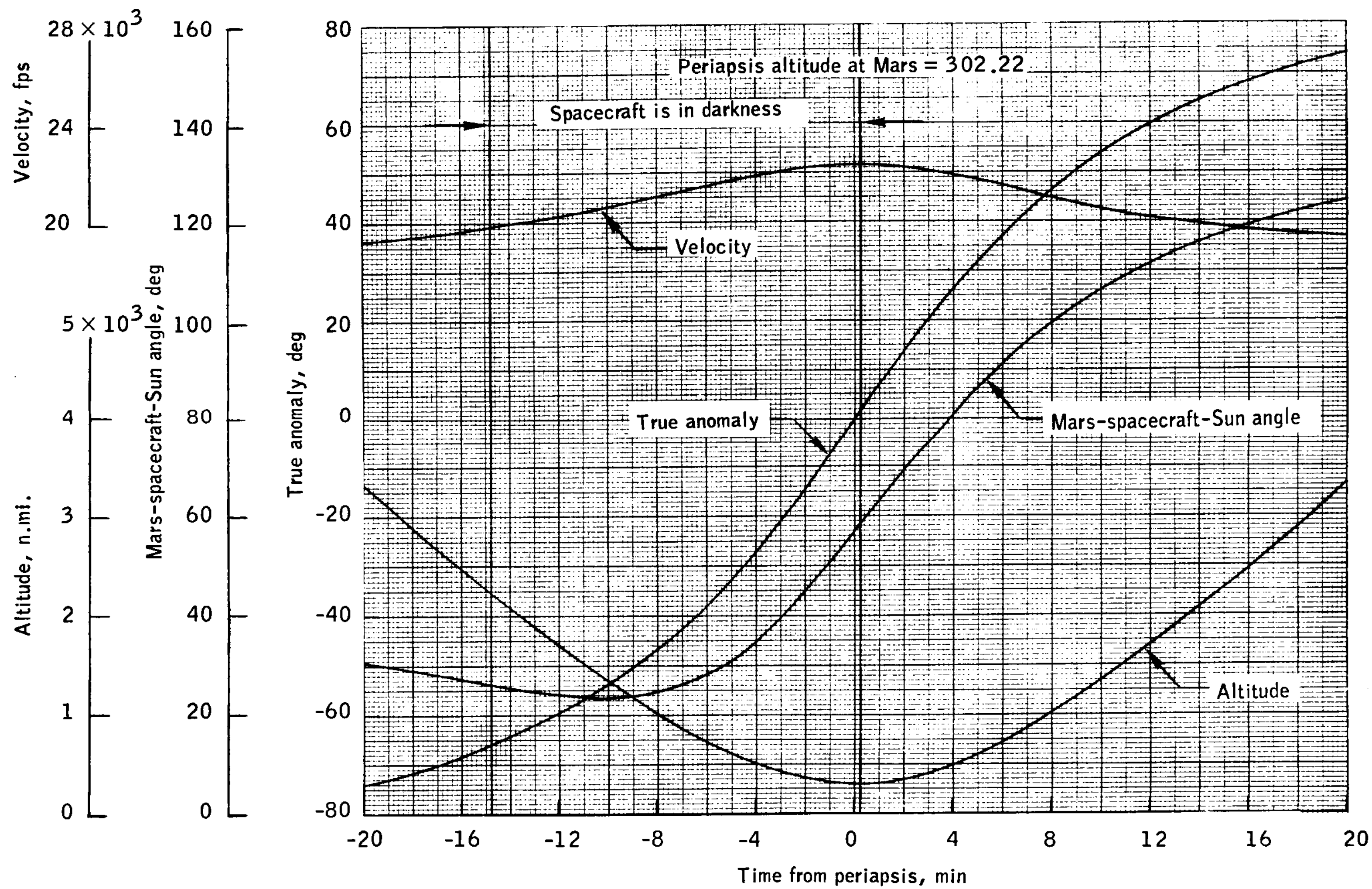


Figure 8.- Motion of spacecraft near Mars when the departure date is December 7, 1978

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